Antenna Measurement Uncertainty Method for Measurements in Compact Antenna Test Ranges

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***Abstract*—Methods for determining the uncertainty in antenna measurements have been previously developed and presented. The IEEE has published IEEE 1720-2012 that formalizes a methodology for uncertainty analysis of near-field antenna measurements. In contrast, approaches to uncertainty analysis for antenna measurements on a compact range are not covered as well in the literature. A review and discussion of the terms that affect gain and sidelobe uncertainty are presented as a framework for assessing the uncertainty in compact range antenna measurements including effects of the non-ideal properties of the incident plane wave. An example uncertainty analysis is presented.**

I. Introduction

The compact range measurement technique was pioneered in the late 1960's as an alternative to far-field antenna measurements [1]. During that time, compact range measurement accuracy was assessed in comparison to well established far-field methodologies. The antenna measurement community has contributed to the understanding of uncertainty in the application of the technique in the technical literature [2, 3, 4, 5, 15]; however, a general framework has not been established to assess the uncertainty of a compact range measurement. The Institute of Electronics and Electrical Engineering (IEEE) has formalized recommendations for near-field antenna measurements which includes uncertainty analysis for the near-field technique [6]. However, there is no equivalent document for compact range antenna measurements. In this paper, the generalized compact range measurement technique will be described and the associated uncertainty terms will be identified. The framework presented can be tailored for use in most compact range antenna measurement systems.

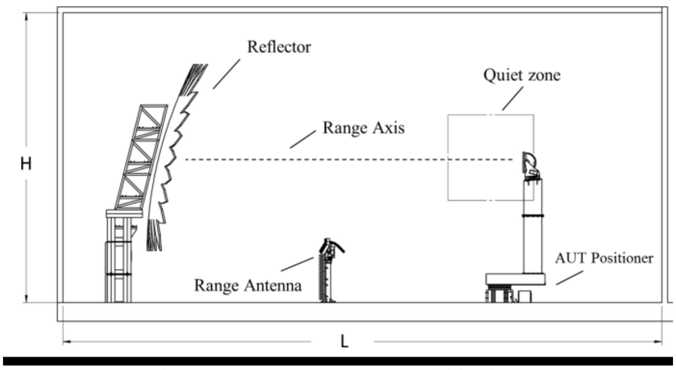

Fig. 1. Compact range geometry (side view)

II. Range Geometry

The compact range system geometry is shown in Fig. 1. The range consists of several subsystems needed for producing an adequate test signal within the quiet zone, positioning the antenna under test (AUT) within the quiet zone, and capturing the microwave data for analysis of AUT performance.

III. Quiet Zone Field Probe

Quiet zone field probes are commonly used to assess compact range performance. The field probe data in Fig. 3 measured in the in-house MI Technologies compact range shown in Fig. 2 will be used in the example uncertainty analysis in Section IV. Three metrics are associated with quiet zone field assessment; amplitude ripple, amplitude taper and phase variation. Amplitude and phase data for Ka-band are shown in Fig. 3 and Fig. 4 respectively. Amplitude ripple is the peak-peak change in amplitude within the quiet zone. Amplitude taper is deviation in field amplitude from a constant value as a function of position within the quiet zone and is assessed using a best fit through the normalized measured field probe data. Phase and amplitude variations are quantified by direct detection of the field within the quiet zone. Using a sensor, usually a standard gain horn antenna or an open ended waveguide, the fields are measured and analyzed [10].

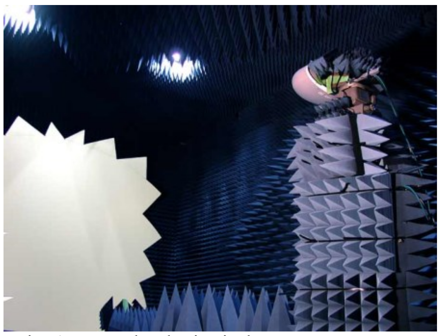

Fig. 1 MI Technologies in-house compact range

The field probe apparatus includes uncertainties associated with the sensor properties and positioning accuracies of the acquisition. The standard gain horn probe pattern will discriminate against stray signals arriving in the quiet zone from wide angles away from the range axis. However, field probe data does provide insight into the quality of the illumination field and are the primary method used to validate range performance. The probe data can be used to examine the effect of stray signals near boresight angles [10].

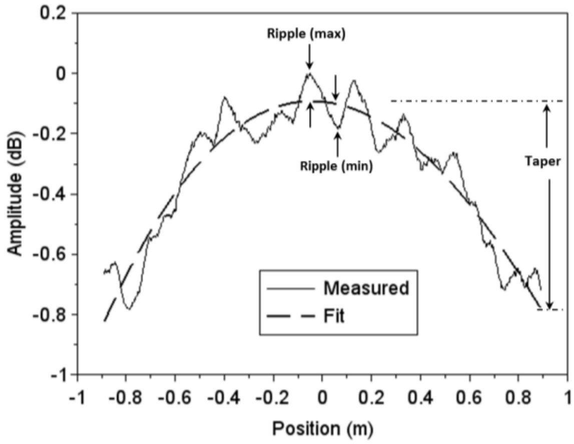

Fig. 2 Field probe amplitude Ka-band H-pol H-cut

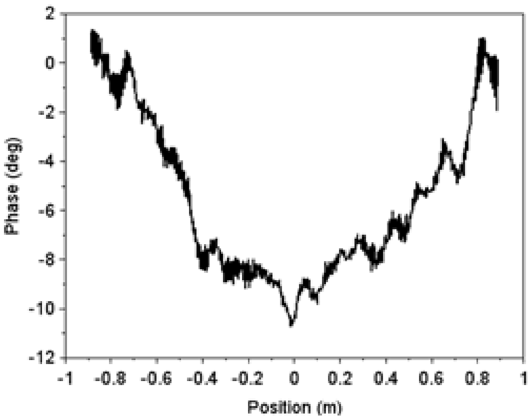

Fig. 3 Measured field probe phase Ka-band H-pol H-cut

IV. Uncertainty Terms and Analysis Example

Example gain and sidelobe uncertainty estimates are provided for an MI Technologies in-house compact range. This range is a center fed offset prime focus reflector using a linear polarized compact range feed antenna and a linear polarized test antenna. The AUT is a Ka-band standard gain horn with maximum diagonal aperture dimension of 10.2cm. The calibration antenna is also a Ka-band standard gain horn. The uncertainty terms in this analysis will be evaluated using conventional techniques as defined in the *Guide to the expression of uncertainty in measurement* [11].

A. Range Antenna Alignment

Proper alignment of the range antenna to the reflector is required to optimize the phase and amplitude performance of the quiet zone. Misalignment will introduce both phase and amplitude errors in the quiet zone field and contribute to gain uncertainty. Phase errors result from the range antenna phase center not being aligned with the reflector focal point such that the spherical phase front from the range antenna is not properly focused by the reflector. The phase center of the range antenna will migrate as a function of frequency so a natural defocusing is expected across the frequency band [7]. For a given size quiet zone and reflector focal length, the quiet zone amplitude taper is largely a function of the range antenna amplitude pattern. However, a small amplitude taper is introduced by the reflector geometry due to the path length difference from the focal point to the center of the reflector and the outer portion of the reflector body.

From Fig. 4, the maximum phase variation over the entire quiet zone is 12 degrees. Over the subject AUT aperture the phase variation is approximately 2 degrees. Using

$$\Delta\phi = \frac{\pi D^2}{4\lambda R}$$

the phase variation is equivalent to $22*D^2 / \lambda$ and is negligible for gain and sidelobe uncertainty [8].

B. Polarization Mismatch

Polarization mismatch of the incident test signal in the quiet zone is due to the range antenna and depolarization effects of the range reflector. Polarization of the gain standard also affects gain measurement uncertainty. Errors can be large if combining two linear polarization measurements in order to synthesize circular polarization [8].

Assuming an ideal linearly polarized standard gain antenna, a range antenna axial ratio of 40dB, and an AUT axial ratio of >25dB, results in a gain uncertainty of **0.009dB** [8].

C. Range Antenna to Quiet Zone Coupling

Direct coupling between the range antenna and the quiet zone can be a source of gain and sidelobe uncertainty. The coupling can be reduced by using an absorber baffle to block the range antenna radiation in the direction of the quiet zone. Estimates of this error can be made by evaluating the range antenna radiation pattern in relation to the range geometry and quiet zone location.

This signal may not be included in the measured field probe since it is off of the range axis. Therefore it will be entered as a separate error. Fig. 5 shows the elevation E and H plane radiation patterns for the range antenna in polar format. The relative position of the quiet zone is approximately 120 degrees from boresight for a center fed prime focus configuration. The signal level relative to the main beam peak in the E-plane pattern is -22dB. The addition of an absorber baffle will attenuate the coupling by an additional 45dB to a level of -67dB. The gain uncertainty associated with this term is +/- **0.004dB** and +/- **0.12dB** for a -30dB sidelobe.

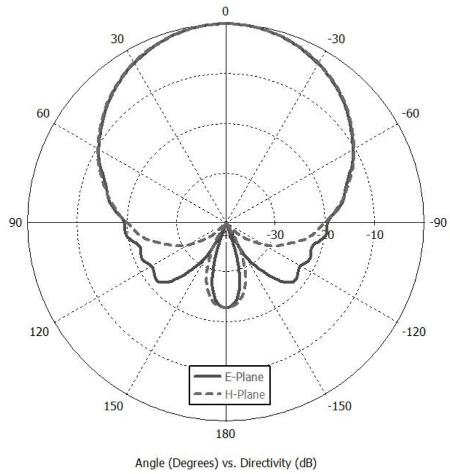

Fig. 4 Range antenna radiation patterns E and H planes

D. *Reflector Terms (Edge Diffraction and Surface Roughness)*

Signal scattering occurs on the reflector due to discontinuities on the reflector surface. At low frequencies, the primary error sources occur at the termination of the reflector when induced surface currents encounter the discontinuity between the reflector and free space. At higher frequencies, reflector surface roughness becomes a contributor; limiting the ability of the reflector to properly collimate the test signal. This effect will limit performance as frequency is increased and the surface features become a significant fraction of wavelength.

A portion of the scattered energy will propagate to the quiet zone and interfere with the primary test signal increasing gain and sidelobe uncertainty. This error term can be assessed by estimating the signal level resulting from the scatter that arrives in the quiet zone to interfere with the primary signal propagating along the range axis. Alternatively, an assessment can be made for a given antenna and a known quiet zone field obtained by a field probe [5].

Referring to Fig. 3, the ripple of +/- 0.1dB can be attributed to an extraneous signal level of -39dB. The field throughout the quiet zone will include many distributed stray signals and a more comprehensive field probe is needed to characterize the stray signal influence. A method of applying measured quiet zone data to a known antenna response has been investigated and can be used to evaluate this uncertainty [5]. This methodology produces a more reasonable estimate of uncertainty than the stray signal approach which tends to be overly pessimistic. However, since the AUT in this example occupies a small fraction of the overall quiet zone, the generally accepted rule of thumb given in IEEE 149-1979 where a taper of 0.25dB results in a 0.1dB uncertainty will be used. The amplitude excursion over the AUT aperture due to ripple is approximately 0.2dB resulting in a gain uncertainty of (0.2dB/0.25dB)*0.1dB = **0.08dB** [8]. Using the results published in reference [5] a -55dB stray signal level will be used resulting in a -30dB sidelobe uncertainty of **+/- 0.5dB**.

E. *Leakage*

Leakage occurs when radiation escapes into the chamber unintentionally and usually occurs at cable interfaces with improper connections, damaged cables or other microwave equipment such as mixers, multipliers, and isolators. Interference within the measurement equipment circuitry due to poor internal isolation between the transmit, reference and receive signals leads to internal cross-talk leakage inside the equipment. Internal cross-talk is characterized by terminating the output of the signal source and the input of the receiver and collecting data as a function of frequency. Leakage is tested by terminating the transmission line at the input of the range feed antenna and collecting data as a function of aspect angle and frequency. Signals detected above the minimum level in the cross-talk test are considered leakage. Leakage terms will introduce stray signal interference in the quiet zone that will be combined with other stray signals in the range. Identifying and reducing leakage sources to a level of -70dB or greater will reduce the gain and sidelobe uncertainty due to this error source.

Leakage was measured by terminating the cable for the transmit range antenna and measuring the system response with a standard gain calibration antenna as the AUT. Leakage will present as increased amplitude levels in the minimum signal level data set, Fig. 6. There is no evidence of significant leakage in the measured data, therefore the uncertainty is **0dB.**

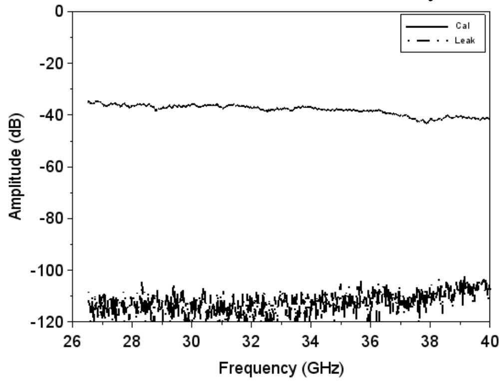

Fig. 5. Minimum and maximum signal measurements

F. *Room Scattering*

Most compact ranges are contained inside of a room lined with microwave absorbing material. The arrangement and type of absorber is selected to attenuate any energy that would otherwise strike the floor, walls, and ceiling and be redirected towards the quiet zone introducing an error and increasing gain and sidelobe uncertainty. Since the angle of arrival of the incoming signal is not typically in the direction of optimum performance of the absorber, some of the energy is reflected and not absorbed. The bistatic reflectivity of absorber can be analyzed to estimate the level of signal scattered towards the quiet zone.

This term may not be adequately captured in the field probe measurement since it arrives at a large angle off of the range axis and may be attenuated by the standard gain horn probe antenna. Therefore it will be accounted for as a separate error term. Fig. 7 shows the reflector radiation pattern with sidelobe energy directed towards the ceiling. The signal level of the sidelobe compared to the main beam signal is approximately -30dB. Using the bistatic scatter curves in Fig. 8 the bistatic scatter for the absorber with thickness of >10λ at Ka-band at an incidence angle of 60º is approximately -45dB resulting in a signal level of -75dB scattered toward the quiet zone. This value is **negligible** for gain and **0.05dB** for a -30dB sidelobe. Additional free-space loss from the absorber to the quiet zone is not accounted for so the estimate is conservative.

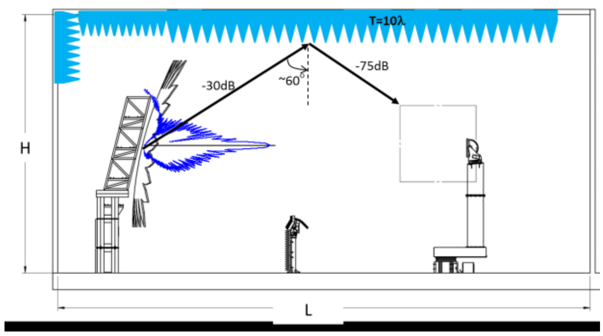

Fig. 6. Bistatic scattering from microwave absorber

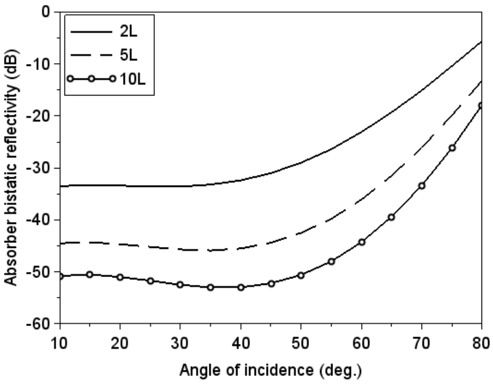

Fig. 7. Bistatic reflectivity for pyramidal absorbers of different electrical thicknesses (L=λ)

G. *Quiet Zone Amplitude Taper*

The range antenna main beam amplitude pattern is projected into the quiet zone and is responsible for the majority of the quiet zone taper [7]. This term affects gain uncertainty.

The amplitude pattern for a typical range antenna is shown in Fig. 9. For a given compact range design application, the reflector is optimized for the given range antenna so that the quiet zone amplitude taper is no more than 1dB. The measured field probe shown in Fig. 3 shows the taper that exists across the quiet zone as a fit to the measured field. Since many antennas characterized in compact range systems do not extend through the entire quiet zone, only the portion of taper across the antenna aperture needs to be considered in the error analysis. Given a 0.8dB taper across the quite zone extent of 1.8m and a maximum AUT dimension of the standard gain antenna of 10.2cm results in an aperture taper of 0.045dB. This taper results in a gain uncertainty of (0.045dB/0.25dB)*0.1dB = **0.018dB** which is lower than the uncertainty calculated for the reflector terms.

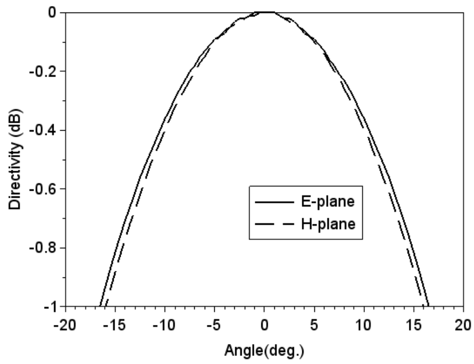

Fig. 8 E&H plane simulated range antenna pattern, Ka-band

H. *Mismatch*

Reflections in the transmission line between the measured antenna and receiver due to the reflection coefficient of each device can introduce uncertainty. This term is present for both the AUT and gain standard antennas. In practice, an attenuator is used to reduce the reflected signal at the expense of dynamic range. Alternatively, the effects of the transmission line reflections can be accounted for mathematically [8, 9]. This term affects the gain uncertainty only.

This mismatch term accounts for reflection coefficients of the AUT (Γ=0.12), standard gain calibration antenna (Γ=0.12), and receiver (Γ=0.17). A 10dB pad was used at the input of the receiver. Using the expression below, the uncertainty contribution is 0.35dB/√2 = **0.247dB** [9, 11].

$$Uncert(dB) = 20\log(1 \pm \Gamma_{AUT}\Gamma_{Rx}) + 20\log(1 \pm \Gamma_{Cal}\Gamma_{Rx})$$

I. *AUT Positioning Errors*

The contribution of position inaccuracies to the overall measurement uncertainty depend on the type of measurement being made. Cross polarization characterizations will be more sensitive to position errors than co-polarization measurements. Measurement processing that combines test signals, such as circular polarization synthesis from two independent orthogonal linear polarization measurements will be more sensitive to position errors. The contribution to the example error analysis is deemed negligible and not further considered.

J. *Receiver Non-Linearity*

Nonlinearity of the microwave receiver will increase the uncertainty of measured sidelobes. This quantity is generally given by the receiver manufacturer as nonlinearity over a specified bandwidth.

Typical values for modern receivers are 0.05dB/decade of dynamic range. Configuring the system for maximum receive level at the pattern maximum, gain uncertainty will be **negligible** and uncertainty for a -30dB sidelobe will be (0.05*3)/√3 = **0.087dB** [11].

K. *Dynamic Range*

Measurement of low amplitude signals becomes more susceptible to errors from leakage and other noise sources in the measurement system. Maintaining a high signal to noise ratio will ensure interference errors are minimized. This term will also affect sidelobe uncertainty as the sidelobe level decreases.

Dynamic range, Fig. 10, is calculated from the maximum and minimum measurements shown in Fig. 6. The dynamic range is in excess of 70dB. Using the stray signal interference model [10], the gain uncertainty is **negligible** and +/-**0.09dB** for a -30dB sidelobe**.**

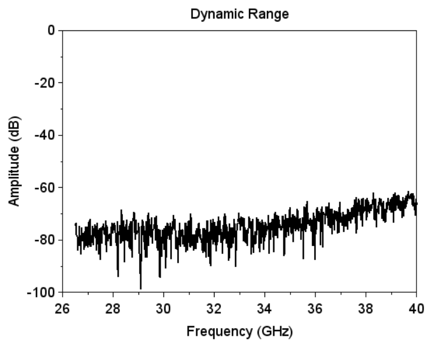

Fig. 9. Dynamic range versus frequency

L. Repeatability

The microwave subsystem contributes errors in both amplitude and phase due to cable flexure, instrument response drift due to changes in temperature and humidity, mixing and multiplexing of the test signal.

Measurements were made by disconnecting and reconnecting the AUT cable ten times to evaluate this error term. Fig. 11 is a plot of the standard deviation for each series of measurements as a function of frequency. Worst case gain uncertainty is **0.022dB.**

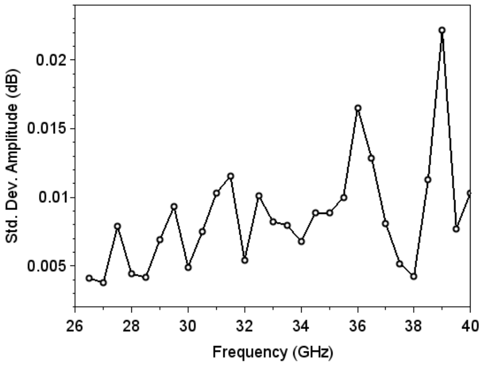

Fig. 10. Repeatability of connection (10x)

M. Multiple Reflections

The scattering cross-section of the AUT can produce a backscattered signal towards the reflector that scatters back to the AUT resulting in an interference term. This error increases as the antenna radar-cross section increases and can be assessed by making measurements with the AUT at different locations along the range axis. This type of measurement can be made using a floor slide to reposition the AUT. For the AUT used in the example, this term is deemed negligible.

N. Gain Standard

Antenna calibration is accomplished by the gain substitution method whereby an antenna of known gain is measured and a correction factor is derived using the differences of the measurement and the known gain of the standard. The gain substitution technique accounts for the transfer function of the entire measurement and compensates for the frequency response of the range. Typically, the standard antenna is measured at the maximum of the standard antenna gain pattern and the computed calibration coefficient is later applied to all subsequent measurements of antennas under test normalizing the AUT pattern to account for the system transfer function. The gain standard has its own uncertainty which must be accounted for in the analysis. The uncertainty can be obtained from the calibration laboratory certificate.

This uncertainty is specified by calibration certificate +/- 0.37dB with coverage factor k= 2 yielding an uncertainty of 0.37/2 = **0.185dB** [11].

O. Other Sources

This term collects other sources of error not accounted for in the previous terms.

TABLE 1. Summary of compact range error sources

No.	Source of Uncertainty	Gain Uncertainty 1σ (dB)	-30dB Sidelobe Uncertainty (dB)
1	Range antenna alignment	0.000	0.000
2	Polarization mismatch	0.009	0.000
3	Range antenna to quiet zone coupling	0.004	0.120
4	Reflector edge diffraction	0.080	0.500
5	Reflector surface roughness	0.000	0.000
6	Leakage and cross-talk	0.000	0.000
7	Room scattering	0.000	0.050
8	Quiet zone amplitude taper	0.018	0.000
9	Mismatch	0.247	0.000
10	AUT positioning system	0.000	0.000
11	Receiver non-linearity	0.000	0.087
12	Receiver dynamic range	0.000	0.090
13	RF Repeatability	0.022	0.000
14	Multiple reflections	0.000	0.000
15	Gain standard	0.185	0.000
16	Other errors	0.000	0.000
	RSS	**0.32 dB**	**0.53 dB**
	Expanded Uncertainty	**0.64 dB**	**1.06 dB**

V. SUMMARY

A general framework has been presented for evaluating compact range antenna measurement uncertainties. The approach is similar to well established uncertainty analysis for planar near-field measurements. Specific aspects such as interference mechanisms associated with the compact range configuration were discussed. This approach can be tailored to various range configurations such as multiple reflector systems. An example uncertainty analysis was presented using measured data to estimate error signal levels.

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